Predicting the Behavior of Graphite/Epoxy Laminates under Hydrothermal Loads

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1 Introduction

The awakening of high thickness composite material structures for aeronautical high level of stress applications explains mainly the comeback of studies about the durability of new brand carbon/epoxy laminates.
Generally, a study on the effects of water is divided in two :

- the study of the propagation of water molecules in the laminate submitted to hydrothermal loads, given by its local concentration c (see [3])
- and, the determination of the effects of c on the local mechanical characteristics of an elementary ply, that will be the purpose of this article.

The durability of organic composite materials is directly linked to the matrix ageing (the fibers are considered as insensitive to hydrothermal ageing), so it was chosen to characterize the evolution of the epoxy matrix Young Modulus (E_m) as a function of c. This part of the study is achieved in two steps:

- the measure of the influence of c on the “simple softening temperature” T_{sr} of the laminate
- and the determination of the effects of T_{sr} on E_m.

Then, the mechanical characteristics of an elementary ply (E_l, E_t, ν_{lt} and G_{lt}) are determined by a series of tests. Once this step done, the use of some “classical” micromechanical laws of recombination allows the inverse determination of the matrix and fibers properties (E_m, E_{f_x}, E_{f_y}, ν_f, and G_f)).
This study is based on experiments realized both at EADS CRC (Suresnes, France) and at ENSICA (Toulouse, France).

2 Experimental Analysis

The beginning of this work was dedicated to the definition of the experimental tests that have been performed. The main idea was to saturate the whole part of the test specimens at the same level of concentration in order to be able to extrapolate easily the local mechanical characteristics from global mechanical tests.
It was chosen to conditionate all the test specimens at three different thermohydrical environments. The temperature is fixed at 70°C in order not to couple thermic and hydrous effects on the tests results, because it does not generate any thermic ageing of the matrix [5] and that, it is one of the basic entry of the material characteristics data base dealing with wet ageing at EADS CRC. The test specimens have been aged at three humidity levels (0%RH[1], 65%RH and 85%RH) that leads to the following wet saturation mass for the **resin** (c_r): 0%, 0.70% and 1.45% (after desorption).

The first step in the determination of the future model is to link the local concentration c to the *simple softening temperature* T_{sr}. This last one is obtained by the mean of a DMA[2] test (in Torsion) and corresponds to the fall of the conservation modulus G'. Two test specimens per humidity conditioning were tested leading to the results presented in table 1.

$\mathbf{c_r}(\%)$	0	0.7	1.45
$\mathbf{T^0_{sr} - T_{sr}(^\circ K)}$	0	29	44

Table 1: T_{sr} function of the local concentration in water molecules of the resin

In [4], a study about Moisture–Temperature equivalence in physical ageing of a carbon/epoxy composite, the importance of the test temperature was underlined. That is why, the mechanical characterization tests were made at three different temperatures (28°C, 70°C and 120°C).
An elementary composite ply is characterized by E_l, E_t, ν_{lt} and G_{lt} and they have been determined by three tests realized on three specific test specimens:

- E_l and ν_{lt}, by traction on unidirectional (0°) test specimens[3]
- E_t, by traction on transverse (90°) test specimens
- G_{lt}, by traction on symmetric–balanced (+/-45°) test specimens

Others test specimens (+/-30°) were also tested (traction) to evaluate the reliability of the models.

[1]Relative Humidity
[2]Dynamical Mechanical Analysis
[3]with the help of a biextensometer

3 MicroMechanical Models and Associated Results

The model used to characterize the effects of c on T_{sr} is the following:

$$\frac{T_{sr}}{T_{sr}^0} = e^{-\beta.c_r} \tag{1}$$

This model is originally applied to the glass transition temperature T_g [2] but as the determination of T_g for wet materials is not enough precise and taking into account that the behavior of T_{sr} regarding wet ageing is the same as T_g, it was decided to apply it to T_{sr}.

The identification of the parameter β is obtained by the use of the results of table 1. The behavior model of E_m regarding to the evolution of T_{sr} is based on [1] and gives:

$$E_m(T_{test}, T_{ref}, c_r) = E_m^0(T_{ref}).\left(\overline{T}\right)^{\beta_E} \tag{2}$$

$$with, \overline{T} = \frac{T_{sr}(c_r) - (T_{test} - T_{ref})}{T_{sr}(c_r = 0)}$$

The results of the whole tests campaign lead to the conclusion that the transverse and shear modulus (E_t and G_{lt}) are the only "wet sensitive" mechanical characteristics of an elementary ply because of the importance of the resin modulus (E_m) in their behavior. The last step consists in recombining the fiber and matrix properties by the mean of the following "classical" micromechanical models [6]:

$$\frac{1}{E_t} = \frac{1}{V_f + \eta_y.V_m}.\left(\frac{V_f}{E_{f_y}} + \eta_y\frac{V_m}{\mathbf{E_m}}\right) \tag{3}$$

$$\frac{1}{G_{lt}} = \frac{1}{V_f + \eta_s.V_m}.\left(\frac{V_f}{G_f} + \eta_s\frac{V_m}{\mathbf{G_m}}\right) \tag{4}$$

$$with, \eta_y = \eta_s = 0,5$$

$$E_l = V_f.E_{f_x} + V_m.E_m \tag{5}$$

$$\nu_{lt} = V_f.\nu_f + V_m.\nu_m \tag{6}$$

All these parameters have been identified via inverse characterization and are summarized in table 2 (it was assumed that the resin has an isotropic behavior).

$\beta_\mathbf{E}$	$\mathbf{E_{f_x}(GPa)}$	$\mathbf{E_{f_y}(GPa)}$	$\mathbf{G_f(GPa)}$	ν_f	ν_m
0.91	240	12	17	0.37	0.35

Table 2: Parameters of the different hydro–micromechanical laws.

The most important results are the evolution of E_m, regarding the test temperature and the moisture conditioning of the material, represented in table 3.

After having evaluated the sensibility of the parameters on the whole model, the results of the(+/-30°) tests were used to control its accuracy, that is of **8.5%** of relative error on the laminate modulus, E_{30}, for the environmental conditioning set.

$\mathbf{E_m/E_m^0}$	T_{ref}=**28°C**	**70°C**	**120°C**
0%RH	1	0.93	0.84
65%RH	0.92	0.91	0.73
85%RH	0.98	0.90	0.65

Table 3: Evolution of E_m versus the environmental conditioning.

4 Conclusions

The evolution of T_g is a good indicator of the material elastic characteristics degradation [5] but the impossibility of its determination for wet materials may lead to the use of another very close parameter the “simple softening temperature” T_{sr} which identification is easier. This parameter could, also, be used in the physical ageing studies, in order to unify these two approaches.
Once the link between the local concentration c and T_{sr} done, the identified micromechanical laws give a good behavior of the “inverse determinated” resin modulus E_m (taking into account the behavior of the matrix surrounded by its interphase and the carbon fibers) which value decrease drastically at elevated functioning temperature (-35% at 120°C and 85%RH). This phenomenom plays a specific role in the decrease of the compression, shear and fatigue characteristics of the whole laminate, that will be the focus of the next study.

References

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